

Geochronology and Geochemistry of Permian Dashizhai Basin in Xing'an-Inner Mongolia Orogen: Implications for the Evolution of the Paleo-Asian Ocean

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ABSTRACT: The Xing'an-Inner Mongolia Orogen is a critical tectonic unit for constraining the evolution of the Paleo-Asian Ocean. However, the location and time of the closure of the Paleo-Asian Ocean are still debated. Here, we select a representative basin in Dashizhai in northeastern China, using U-Pb zircon geochronology and geochemistry to analyze the sedimentary facies, depositional ages, and provenance. The results show that the ages of the Dashizhai Formation range from 400 to 347 Ma, the Shoushangou Formation range from 400 to 348 Ma, the Zhesi Formation range from 307 to 252 Ma, and the Linxi Formation range from 299 to 241 Ma. The Dashizhai Formation is composed of metamorphic andesite and clastic rocks. The Shoushangou Formation comprises siltstone, rhyolite, and argillaceous siltstone. The Zhesi and Linxi Formations are composed of mudstone and argillaceous siltstone. Geochemical data shows that these rocks are enriched in light rare earth elements and depleted in Eu with various La/Sc, Th/Sc, and La/Co ratios. The Permian Dashizhai Basin is from Permian volcanic and felsic igneous rocks from the Ergun, Xing'an, and Songliao blocks. The absence of the Late Carboniferous strata in the Dashizhai Basin indicates an extension setting during this period. Furthermore, we suggest the Xing'an-Inner Mongolia Orogen was an uplifting process associated with evolution the Paleo-Asian Ocean during the Late Permian.

KEY WORDS: zircon, U-Pb age, geochemistry, Permian basin, Xing'an-Inner Mongolia Orogen, Paleo-Asian Ocean, depositional provenance.

0 INTRODUCTION

The Xing'an-Inner Mongolia Orogen is located in the east part of the Central Asian Orogenic Belt, which is associated with the closure of the Paleo-Asian Ocean between the North China and Siberia cratons (Wu et al., 2021, 2016a, b; Wang, 2020; Xiao et al., 2017, 2003; Li et al., 2016; Li, 2006; Şengör et al., 1993). The Hegenshan ophiolite mélangé in the Xing'an-Inner Mongolia Orogen is the product of the converging of Xing'an and Songliao-Xilinhot blocks at 320 Ma (Liu et al., 2017; Wang, 2008). The Solonker-Xilamulun ophiolite mélangé is the suture zone between the Jiameng Block and the North China Craton (Wang et al., 2017; Liang et al., 1994). The Xing'an-Inner Mongolia Orogen can be divided into four blocks from northeast to southwest, including the Ergun, Xing'an, Songliao, and Jiamusi blocks (Fig-

ure 1; Chen et al., 2018; Zhou et al., 2018; Wang et al., 2012; Wu et al., 2011, 2007; Zhou et al., 2009; Ge et al., 2007a, b). The study area is located in the Hegenshan-Heihe structural zone, which is the conjunction zone between the Xing'an and Songliao blocks (Figure 1).

The Xing'an-Inner Mongolia Orogen includes three lithotectonic belts resulting from divergent subduction of the Paleo-Asian Ocean, including the northern accretionary zone, the Solonker suture zone, and the southern accretionary zone (Li et al., 2019, 2017, 2014; Liu et al., 2017; Xiao et al., 2003). The northern accretionary zone can be subdivided into the Hegenshan ophiolite and the Baolidao arc-accretion complexes. The southern accretionary zone can be subdivided into the Ondor Sum subduction-accretion complex and the Bainaimiao arc (Li et al., 2019, 2017, 2014; Xiao et al., 2003). Four end-models for the evolution of the Paleo-Asian Ocean have been mentioned: (1) The closure of the Paleo-Asian Ocean was in the Late Paleozoic and formed a younger continental crust. An Upper Carboniferous – Permian epicontinental sea or rift was above the continental crust rather than an open ocean (Zhao et al., 2016; Shao et al., 2014; Xu and Chen, 1997; Shao, 1991; Cao et al., 1986). (2) The ocean

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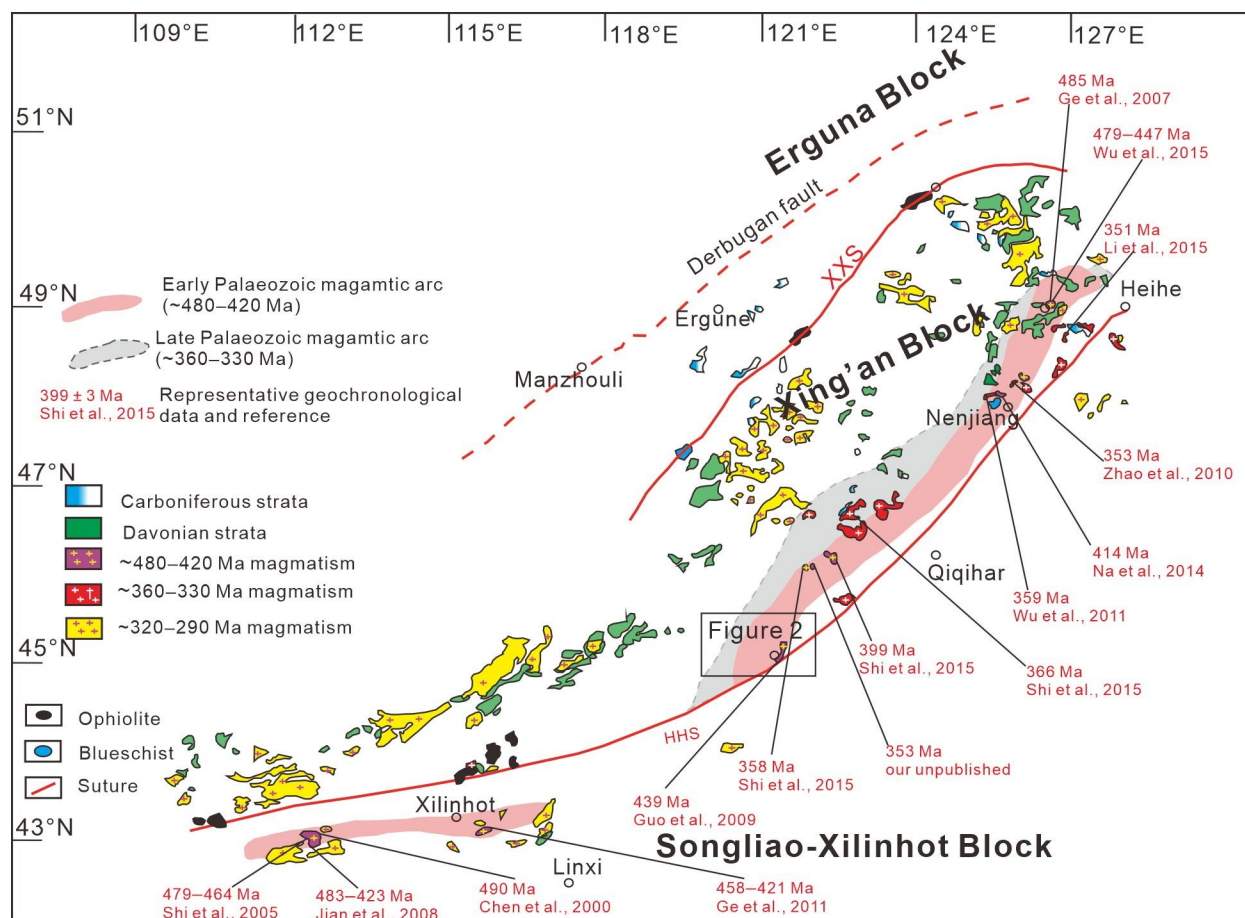


Figure 1. (a) Tectonic framework of the central-eastern segment of the Central Asian Orogenic (modified after Zhang et al., 2015); (b) geologic sketch map in NE China (after Zhou et al., 2019).

closing was related to multiple subduction-collision processes with the final closure in the Late Permian–Early Triassic (Wilde, 2015; Xiao et al., 2015, 2003; Cao et al., 2013; Jian et al., 2010; Zhang et al., 2009, 2007; Miao et al., 2008; Chen et al., 2000; Hsu et al., 1991). (3) The closure of the Paleo-Asian Ocean was in the Middle Triassic (Xiao et al., 2017; Li H Y et al., 2016; Li J Y et al., 2007). (4) The closure of the Paleo-Asian Ocean was in the Late Devonian–Early Carboniferous with several new oceanic basins in the Late Carboniferous–Permian (Zhao et al., 2018; Ma et al., 2017; Yang et al., 2017; Luo et al., 2016; Song et al., 2015; Zhang et al., 2014; Chen et al., 2012).

The tectonic evolution of the Late Carboniferous–Permian sedimentary basins in the Xing'an-Inner Mongolia Orogen plays a key role in the above debate. The development of clastic rock containing continental plant fossils in the Late Permian can provide the formation age and sedimentary environment of the strata, and the structural information contained therein can reveal the Permian evolution process of the Xing'an-Inner Mongolia Orogen (Zhou et al., 2018). Three different mechanisms for interpreting the basin have been mentioned: (1) A residual sea tectonic setting after the closure of the Paleo-Asian Ocean (Wu, 2014); (2) a back-arc basin associated with the subduction of the Paleo-Asian Ocean along the

Solon-Xilamulun tectonic belt (Wang et al., 2021; Zhang et al., 2015; Liu, 2009); (3) newly oceanic basin or rift formed by extension during Late Paleozoic (Shao et al., 2019; Tong et al., 2015).

In this contribution, we present constraints on the structural framework of the sedimentary facies, formation ages, and provenance of the Permian Dashizhai Basin based on a compilation of results from new geochronology and major- and trace-element geochemistry. Our results allowed us to determine the evolution of the Xing'an-Inner Mongolia Orogen during the Late Paleozoic. Further, the Dashizhai Formation in the Wuchagou area was also analyzed to constrain the tectonic boundary associated with the evolution of the Paleo-Asian Ocean.

1 GEOLOGIC SETTINGS

1.1 Regional Geology

The Dashizhai Basin is located in the eastern part of the Xing'an-Inner Mongolia Orogen, which can be divided into four blocks from northeast to southwest, including the Ergun, Xing'an, Songliao, and Jiamusi blocks (Figure 1). These blocks are separated by Xinlin-Toudaoqiao structural zone (Chen et al., 2018; Ge et al., 2007a, b), Hegenshan-Heihe structural belt (Zhou et al., 2018; Wu et al., 2011), and Yilan-Yitong fault, respectively (Wang et al., 2012; Wu et al., 2011, 2007; Zhou et al., 2009). The

study area is located in the Hegenshan-Heihe structural zone, which is the conjunction zone between the Xing'an and Songliao blocks (Figure 1).

The Xing'an Block consists of the Cambrian Xinkailing and the Wolegen groups, followed by the Ordovician Tongshan, Silurian Niyuhe, and Devonian Daminyan Groups. Early Paleozoic arc magmatic rocks are developed at the southern margin (Li et al., 2016). These magmatic rocks in the Xing'an Block have a peak range from 537 to 440 Ma (Sun et al., 2014). Intrusions in the east part of the Xing'an Block have the ages of $2\,579 \pm 15$ Ma (Qian et al., 2018) and $1\,837 \pm 5$ Ma (Zhang et al., 2018).

The Songliao Block consists of the Xilingol Complex. This complex contains quartzite, mica quartz schist, marble, biotite plagioclase gneiss, and felsic gneiss with the metamorphism of the greenschist facies and amphibolite facies in the Early Paleozoic (Liu et al., 2003; Li and Gao, 1995), and unconformably overlain by Late Paleozoic Carboniferous and Early Permian sedimentary rocks (Zhao et al., 2016). The Neoproterozoic magmatic rocks were yielded the zircon U-Pb ages of ~ 1.4 Ga (Sun et al., 2020, 2018). Early Paleozoic arc-magmatic rocks are located along the Sunitezuoqi-Xilinhote belt on the northern margin of the Songliao Block (Jian et al., 2008; Shi et al., 2005; Chen et al., 2000) with the zircon U-Pb ages of ~ 350 Ma. The age range of Late Paleozoic magmatic rocks is from 321 to 237 Ma (Wu et al., 2011).

Hegenshan-Heihe fault was formed by the Late Carboniferous–Permian sedimentary strata transition from marine to continental facies during Late Paleozoic (Wu et al., 2007). Yilan-Yitong fault is considered associated with the Heilongjiang Complex. The deformation and metamorphism ages of the Heilongjiang Complex were constrained by the Early Jurassic (Wu et al., 2007).

1.2 Late Paleozoic Strata

Late Paleozoic strata in the Xing'an-Inner Mongolia Orogen includes the Upper Carboniferous Shuamazuang and Permian Sanmianjing Formations separated by the Suolun-Xilamulun fault. Elitu and Yujiabeigou formations are developed on the northern margin of the North China Craton (Shao et al., 2014; Wu, 2014).

Continental sedimentary strata include Upper Carboniferous Benbatu and Amushan formations, Early Permian Dashizhai and Shoushangou Formation clastic rocks with volcanic rocks, as well as marine sedimentary rocks. Middle Permian Zhesi Formation clastic rocks consist of carbonates lithofacies strata and clastic sea-terrestrial strata. Late Permian Linxi Formation is on the northern margin of the North China Craton. The strata of the Late Paleozoic are unconformity contact with the underlying strata (Zhao et al., 2016). Marine strata develop the Erlian-Hegenshan structure zone in the south. The Carboniferous to Permian Baoligaomiao and Gegenaobao continental volcanic rocks intercalated with clastic rocks are in the north.

2 STRATA IN THE DASHIZHAI BASIN

The Late Paleozoic sedimentary basins extend northward in the Dashizhai area (Figure 2). The long axis is consistent with the Dashizhai tectonic mélange. The strata include Early Permian Shoushangou and Dashizhai, Middle Permian Zhesi, and Late Permian Linxi formations (Figure 3). The Lower Permian sedimentary rocks contact with the Dashizhai tectonic mélange, whereas the Middle Permian is unconformable contact with the tectonic mélange.

2.1 Dashizhai Formation

The Dashizhai Formation is composed of light gray-white schistosity altered dacite, light green-gray schistosity altered andesite, schistosity crystalline tuff, light gray altered dacite, and light green-gray altered andesite (Figure 3). Andesite (Figure 4a) and metamorphic clastic rocks (Figure 4b) are distributed in the Wuchagou area, 80 km northwest of Dashizhai. The sample of silty slate (18SL07-b1, Figure 5a) was collected from the northeast of Wuchagou. The fresh rocks are dark gray with a plate-like texture. The rocks consist of quartz, feldspar, and cementing material. The grain sizes range from ~ 0.005 to 0.05 mm with 65%–70% content. The cement is residual clay with a range of 30%–35%.

The fresh clay silty slate (18SL08-b1, Figure 5b) is gray-green with plate-like and variable-layered textures. The rock consists of quartz and feldspar. The cement, with a range of 40%–45%, is composed of clay minerals. The grain sizes range from ~ 0.005 to 0.05 mm with 55%–60% content.

The fresh gray-green andesitic tuff (18SL06-b1, Figure 5c) is gray-brown with porphyritic and massive textures. The phenocrysts are composed of plagioclase ($15\% \pm$) and clinopyroxene ($2\% - 3\%$), with the particle size of $0.2 - 2$ mm. Plagioclase is subhedral platy with rare kaolinite and sericite alteration. Clinopyroxene is subhedral with local green ordinary petrification. The cement (80%–85%) consists of plagioclase with rare kaolinite, sericite, and quartz. The grains are subhedral with a size of less than 0.1 mm.

The fresh clay silty contact metamorphic slate (18SL05-b1, Figure 5d) is green-gray with plate-like textures. The rock is composed of quartz and feldspar. The cement with a 30%–35% content comprises clay minerals with the oriented long axis. The size of the minerals ranges from 0.005 to 0.05 mm with a content of 65%–70%.

2.2 Shoushangou Formation

The Shoushangou Formation is distributed along with the Dashizhai tectonic mélange (Figure 3). The rocks of the Shoushangou Formation can be divided into two units. The lower unit consists of metamorphic gravel-bearing coarse-grained quartz sandstone intercalated with metamorphic sandstone siltstone and metamorphic argillaceous siltstone (Figure 4c). The upper unit is light gray metamorphic tuffaceous sandstone, serialized silty

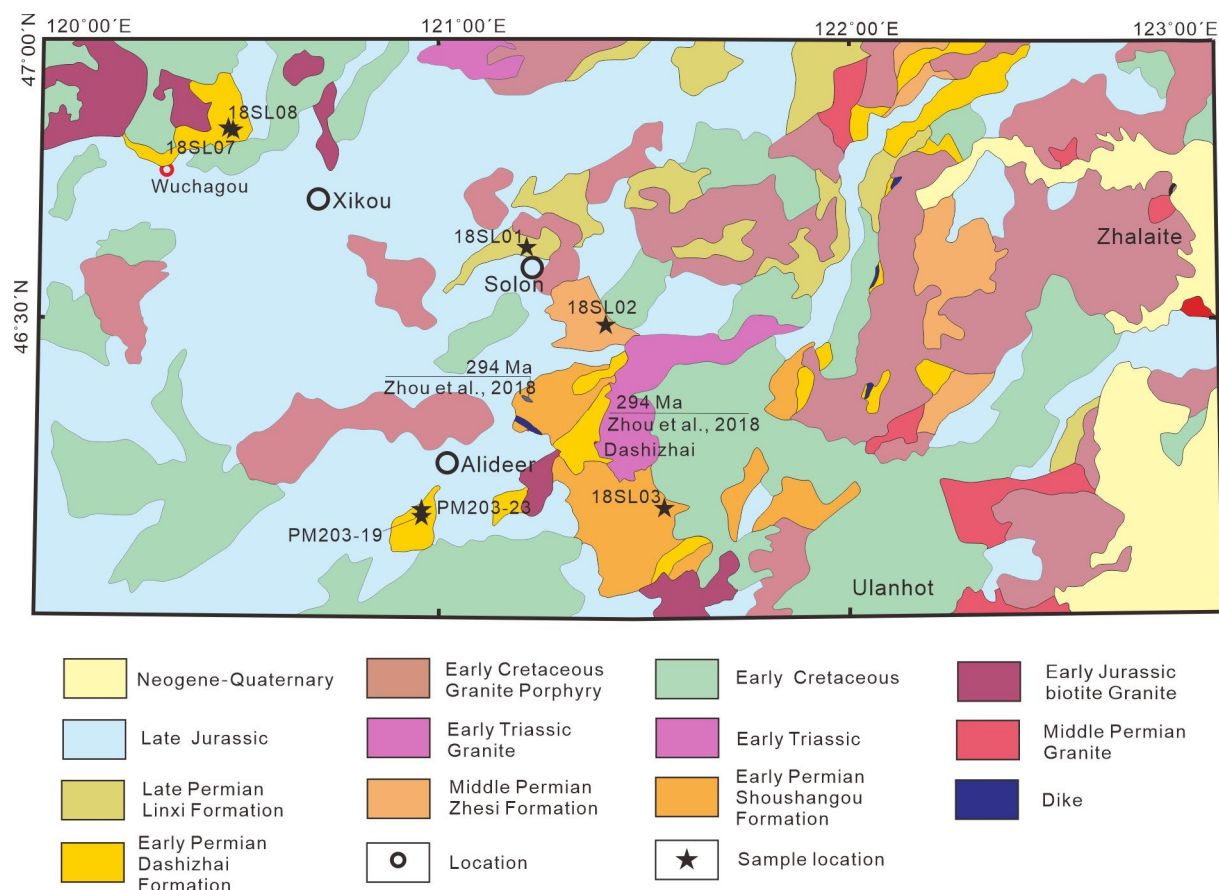


Figure 2. Geologic map in Dashizhai Basin with sample locations.

slate, silty slate, and argillaceous siltstone with a small amount of sandy slate rock (Figure 4d). The Shoushangou Formation is intruded by the Late Permian granite, the Jurassic granodiorite, and the Early Cretaceous granite.

The schistotic rhyolite (PM203-9, Figure 5f) is gray-white with residual porphyritic-matrix microcrystalline texture. The phenocrysts consist of potassium feldspar, plagioclase, and quartz, with a 0.2–3.5 mm grain. Potassic feldspar has a content of $15\% \pm$ and plagioclase has a content of $20\% \pm$. Quartz is in the shape of granular with a 5%–10% content. The matrix is composed of felsic minerals which are oriented in fine lines and stripes around the phenocrysts with size of less than 0.2 mm. Tiny amount sericite and biotite are relatively aggregated in striped and linear oriented.

The fresh tuffaceous silty slate (18SL03-b1, Figure 5e) is dark gray with medium-fine-grained and plate-like textures. The rock is composed of quartz (20%–25%), feldspar (15%+) and matrix (55%–60%). Quartz and feldspar are subhedral grains with a directional arrangement. The interstitial material is tuffaceous (< 5%), which is metamorphosed into micro-scale sericite and biotite.

2.3 Zhesi Formation

The Middle Permian Zhesi Formation in the Dashizhai area is unconformable with the underlying Dashizhai tectonic mélange. The Zhesi Formation consists of dark gray metamorphic mudstone, silty mudstone, and argilla-

ceous siltstone intercalated with carbonate rocks (Figure 3). A small amount of gray-green metamorphic layered (with gravel) and medium-fine lithic sandstone are in the lower part (Figure 4e). The upper part includes thick, sand-bearing crystalline limestone, limestone, bioclastic limestone, and argillaceous siltstone. Limestone and bioclastic limestone include sea lily stems, bryozoans, brachiopods and other marine philosophers. Paleontological fossils are Sri Lanka fauna (Figure 4f). The paleontological fossils collected in this work are brachiopods. The fossil assembly can be compared with the standard section of the Zhesi fauna.

The fine-grained metamorphic feldspar lithic sandstone (18SL02-b1, Figure 5g) is dark gray with fine-grained sand-like textures. The minerals are quartz ($15\% \pm$), feldspar (20%–25%), and cement ($60\% \pm$), with the size range of 0.05–0.2 mm. Quartz is mostly single crystal. Cements show an aggregate of particulate felsic, sericite, and chlorite. Secondary minerals are kaolinite, sericite, and limonite.

2.4 Linxi Formation

The Upper Permian Linxi Formation is widely distributed in the Permian Sedimentary Basin of Dashizhai (Figure 3). The main rocks are composed of the weakly metamorphic silty mudstone, argillaceous siltstone, and fine-grained lithic sandstone (Figure 4g), with partial horizontal bedding or fading spots (Figure 4h). The metamorphic

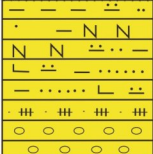
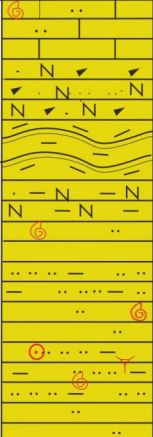
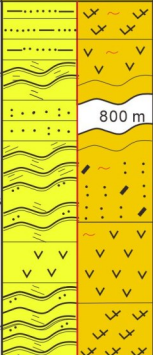
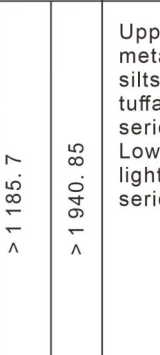
Formations	Code	Stratigraphic pillar	Thickness (m)	Lithology
Linxi Formation	P ₃ I		> 531.5	Upper: gray metamorphic siliceous silt-bearing mudstone, metamorphic siliceous, silty, fine-grained feldspar sandstone, metamorphic calc-siliceous, argillaceous siltstone; Lower: conglomerate, mixed sandstone
Zhesi Formation	P ₂ zs		> 1 464.2	Argillaceous slate, feldspar lithic sandstone intercalated with limestone lens, metamorphic argillaceous feldspar sandstone, silty silty limestone containing biological clastics, weakly metamorphic argillaceous calcareous siltstone containing biological clastic powder Sandy silty crystalline limestone, Fossil in limestone: <i>Dielasma sp.</i> , <i>Neaspirifer sp.</i> , <i>Schuchertella sp.</i> , <i>Spiriferellina sp.</i> , <i>Pseudomarginifera sp.</i> , <i>Martinia sp.</i> , <i>Hustedia sp.</i> , <i>Martinia sp.</i> , <i>Cancrinella sp.</i> , <i>Neaspirifer sp.</i> , <i>Alispiriferella sp.</i>
Shoushangou Formation	P ₁ ss		800 m	Upper: metamorphic argillaceous siltstone. metamorphic tuffaceous sandstone, sericite slate Lower: sericite slate. light gray-gray black silty sericite slate, and andesite
Dashizhai Formation	P ₁ ds		> 1 185.7	Schistological altered dacite, schistological altered andesite. schistological crystalline tuff, altered dacite, massive altered andesite
			> 1 940.85	

Figure 3. Permian four stratigraphic unit of Dashizhai Basin.

siltstone of the Linxi Formation is rich in animal and plant fossils.

The metamorphic fine-grained lithic sandstone (18SL01-b1, Figure 5h) presents gray-black in color. The rocks are composed of quartz and feldspar with the size of 0.05–0.25 mm. Quartz (15%±) is euhedral grain. Cement (65%±) consists of sericite and chlorite. The secondary minerals include kaolinite, sericite, and limonite.

3 SAMPLING AND METHODS

Fresh samples were collected in the field. Zircons were separated at the laboratory of the Hebei Provincial Regional Geological and Mineral Investigation Institute. The samples were washed, dried, crushed, and then washed with water. After electromagnetic sorting, delicate washing is carried out with alcohol. Zircons were picked up under a microscope. Zircon cathodoluminescence (CL) and reflected light images were conducted at the Beijing Zhongke Mining Research and Testing Technology. Zircon U-Pb isotope age analysis was conducted at the Tianjin Institute of Geological Survey of Mineral Resources with the Neptune LA-MC-ICPMS instrument and a 193

nm laser. The laser ablation spot beam diameter is 35 µm and the laser ablation depth is 20–40 µm. GJ-1 is used as the external standard for U-Pb isotope correction, and the NIST612 glass is used as an external standard to calculate the Pb, U, and Th concentrations (Li et al., 2009). The data is processed using the ICPMSDataCal program (Liu et al., 2008), and the age calculation is performed by Isoplot (version 3.0) (Ludwig, 2003) software.

Fresh samples with 200 meshes were fragmented at the laboratory of the Hebei Provincial Regional Geological and Mineral Investigation Institute. Geochemical analysis was conducted at the Chinese Academy of Geological Sciences laboratory. The major element analysis is referred by GB/T14506 silicate chemical analysis. The trace elements were conducted by X Series 2 inductively coupled plasma mass spectrometry (ICP-MS) with an analysis accuracy better than 5%.

4 RESULTS

4.1 U-Pb Dating

In this study, representative zircon CL images are shown in Figure 6. The ages of silty slates from Dashi-

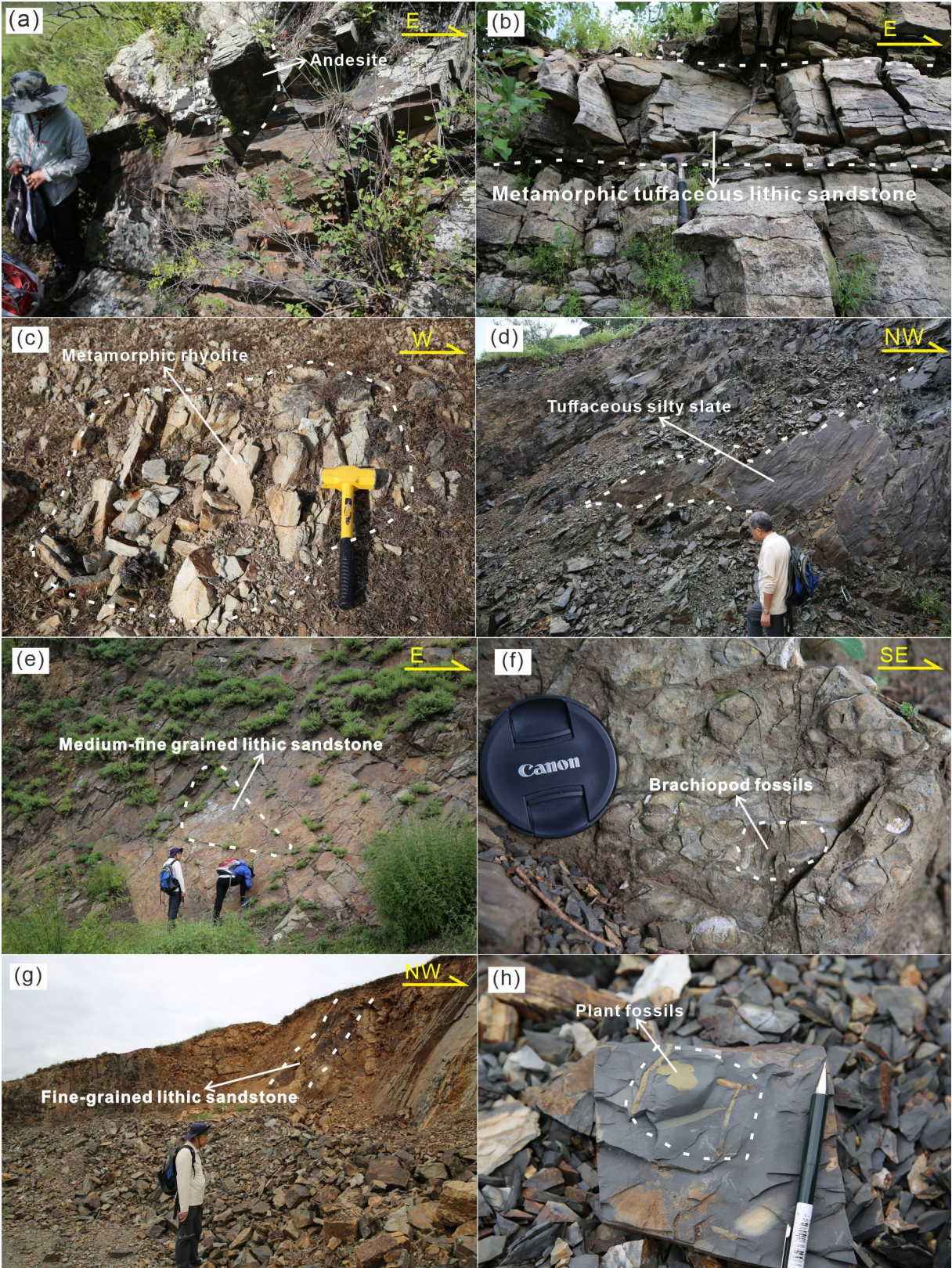


Figure 4. Photos of samples in Dashizhai Basin. (a) Andesite; (b) metamorphic clastic rocks (collected from the Dashizhai Formation); (c) metamorphic rhyolite; (d) silty slate (collected from the Shoushangou Formation); (e) medium-fine lithic sandstone; (f) paleontological fossils (collected from the Zhesi Formation); (g) fine-grained lithic sandstone; (h) plant fossils (collected from the Linxi Formation).

zhai Formation, silty slates and rhyolites from Shoushangou Formation, siltstone slates from Zhesi Formation, and lithic sandstone from Linxi Formation are summarized in Table 1.

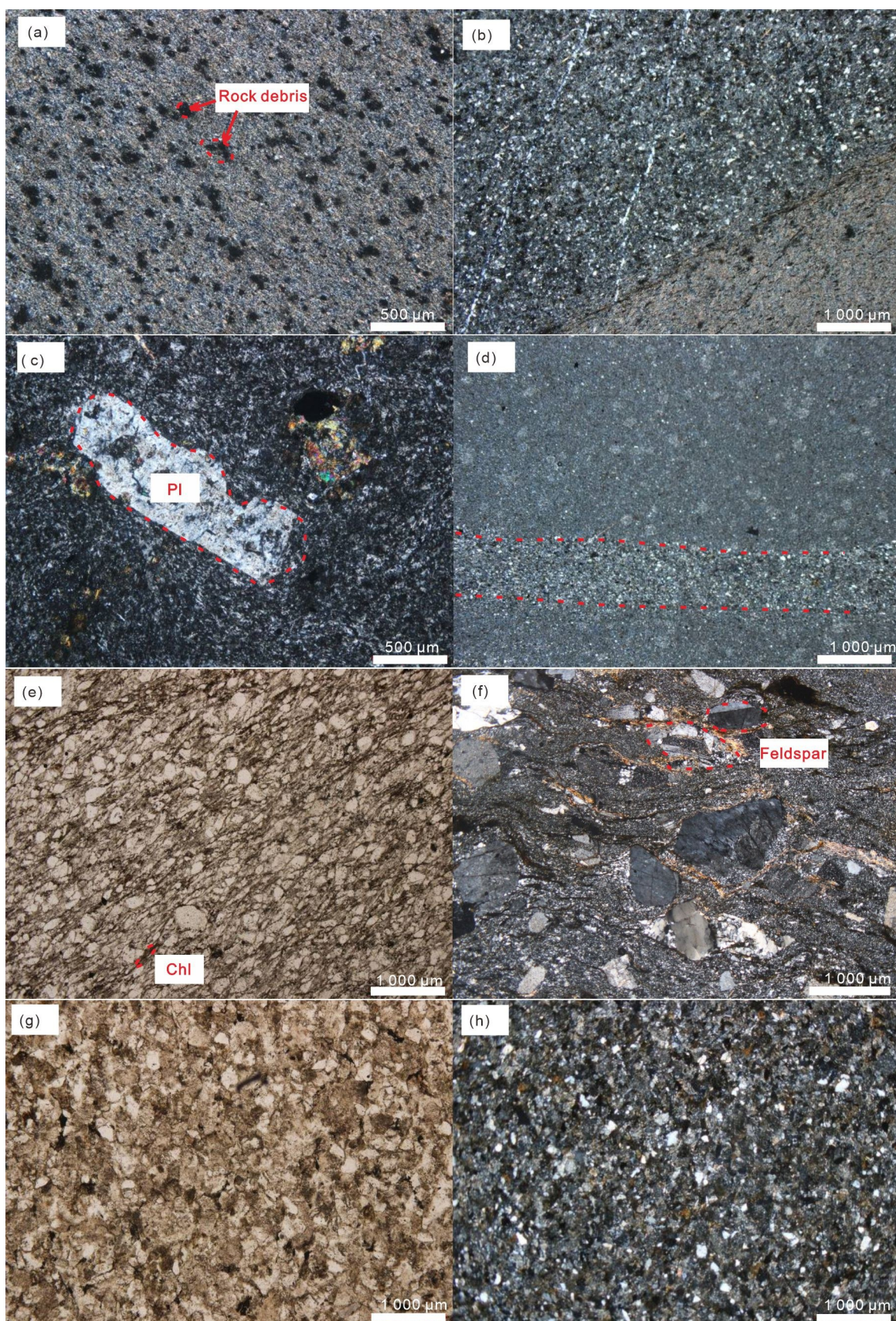


Figure 5. Microscopic photos of samples in Dashizhai Basin. (a), (b) Silty slate; (c) andesite; (d) silty with metamorphic slate (collected from the Dashizhai Formation); (e) tuffaceous silty slate; (f) rhyolite (collected from the Shoushangou Formation); (g) feldspar lithic sandstone (collected from the Zhesi Formation); (h) fine-grained lithic sandstone (collected from the Linxi Formation).

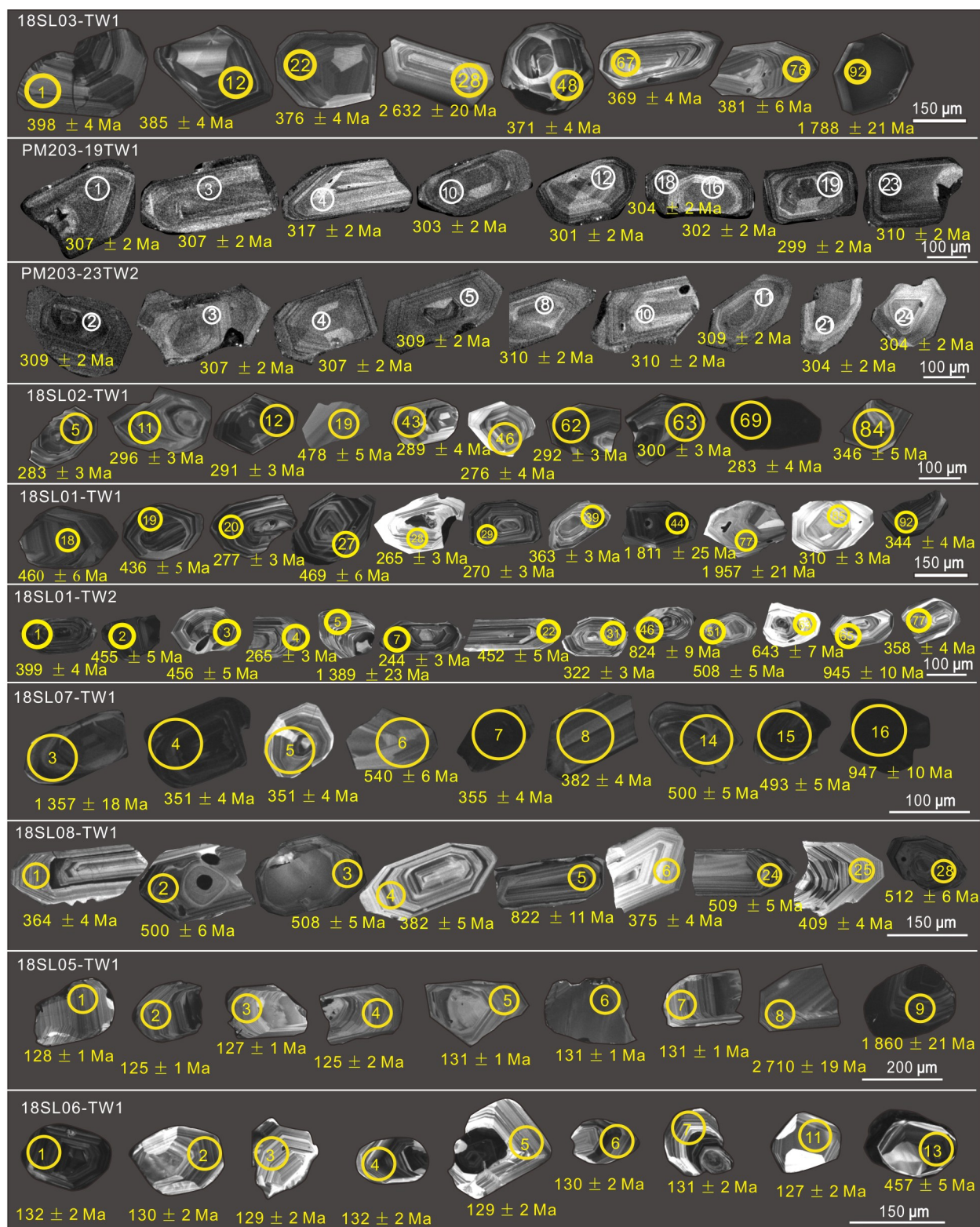


Figure 6. Representative zircon cathodoluminescence images.

4.1.1 Dashizhai Formation

The zircons of silty slates from the northeast of Wuchagou (18SL07-TW1 and 18SL08-TW1) are short columnar and round (Figure 6). The sizes of the zircon range from 100 to 300 μm with an aspect ratio between 4 : 1–1 : 1. The internal texture of zircon has an obvious

oscillatory growth. These zircons have a magmatic origin with the Th/U ratios of 0.21–2.20. Sixty-three zircons from two samples were dated by LA-ICP-MS (Table S1). These ages are summarized in 5 ranges, including 360–320 Ma ($n = 5$), 400–360 Ma ($n = 29$), 520–480 Ma ($n = 11$), 960–800 Ma ($n = 5$), and 1 480–1 400 Ma ($n = 2$).

Table 1 Formation, rock, and age from Dashizhai Basin

Formation	Rock	Age (Ma)
Linxi Formation	Lithic sandstone	241
Zhesi Formation	Silty slates	252
Shoushangou Formation	Rhyolite	305–303
	Tuffaceous argillaceous slate	348
Dashizhai Formation	Silty slate	351

The youngest zircon age is 351 Ma, indicating that the depositional age of the Dashizhai Formation is constrained to be no earlier than 351 Ma (Table S1, Figure 7).

The zircons of the silty slate (18SL05-TW1) of the Dashizhai Formation in the Shuipaodangou of Wuchagou area are short columnar or muddy round (Figure 6). The size ranges from 100 to 180 μm , and the aspect ratio is between 2 : 1 and 1 : 1. The internal texture of the zircon has an apparent oscillating growth zone with a Th/U value of 0.28–2.53. The age spectrum is distributed in 3 groups (Figure 7), which are 132–116 Ma ($n = 19$), 2 264–1 860 Ma ($n = 4$), and greater than 2 600 Ma ($n = 2$). The youngest group has an average age of 128.0 $\pm$ 2.4 Ma (MSWD = 2.8).

The zircons of andesite (18SL06-TW1) in Er-musitaigou of Wuchagou area are mostly spherical (Figure 6), with a size of 80–150 μm . The aspect ratio of about 1 : 1 and the internal texture of the zircon has an apparent oscillating growth zone with a Th/U value of 0.32–1.82. The zircons have a magmatic origin, and a few zircons lose Pb due to thermal contact metamorphism. LA-ICP-MS dating of 29 zircons was performed on the sample (Table S1). The data are located on or below the concordia line (Figure 7). The age of the upper intersection is 126.6 $\pm$ 2.6 Ma, representing the formation age of the rocks.

4.1.2 Shoushangou Formation

The zircons of the tuffaceous argillaceous slate (18SL03-TW1) of the Lower Permian Shoushangou Formation (18SL03-TW1) are colorless with short columnar. The zircons have a grinding circle with a size of 80–250 μm . The cathodoluminescence image (Figure 6) shows a zonal texture, except for the zircons with an age of about 400 and 1 800 Ma. The Th/U ratios range from 0.06 to 5.48. The LA-ICP-MS dating of zircons has obtained 100 ages (Table S1, Figure 8), which can be divided into five groups, including 358 $\pm$ 4–348 $\pm$ 4 Ma ($n = 6$) with the peak value of 352 $\pm$ 4, 412 $\pm$ 4–361 $\pm$ 4 Ma ($n = 91$) with the peak value of 380 $\pm$ 4, 543 $\pm$ 6 ($n = 1$), 1 788 $\pm$ 21 Ma ($n = 1$), and 2 632 $\pm$ 20 Ma ($n = 1$). The youngest zircon age is 348 Ma, indicating that the depositional age of the Shoushangou Formation is not earlier than the Early Carboniferous.

Two rhyolite samples (Table S1) from the Lower Permian Shoushangou Formation were dated (PM203-19TW1, PM203-23TW1). The zircons are columnar with

an aspect ratio of 2 : 1–4 : 1. The cathodoluminescence image (Figure 6) shows a clear zonal texture. The Th/U ratios are 0.35–0.73, indicating that those zircons have a magmatic origin. The sample PM203-19TW1 was dated with 23 zircons (Figure 8). The average age of $^{207}\text{Pb}/^{238}\text{U}$ is calculated as 303.4 $\pm$ 1.3 Ma (MSWD = 2.3), representing the age of dacite. A total of 25 zircons dating was obtained from sample PM203-23TW1 (Figure 8). The average age of $^{207}\text{Pb}/^{238}\text{U}$ is 305.7 $\pm$ 1.3 Ma (MSWD = 2.1).

4.1.3 Zhesi Formation

The zircons of the silty slate of the Middle Permian Zhesi Formation (18SL02-TW1) are colorless and transparent, with an aspect ratio of about 1 : 1. The zircons are 60–120 μm . The cathodoluminescence image (Figure 6) shows a clear zonal texture. The Th/U ratios are 0.32–1.74. The LA-ICP-MS dating of 100 zircons of samples has obtained (Table S1), and the age spectrum shows three groups of peak ages (Figure 9), including 279 $\pm$ 4 Ma ($n = 86$), 304 $\pm$ 4 Ma ($n = 11$), and 478 $\pm$ 5–453 $\pm$ 4 Ma ($n = 2$). The youngest age is 252 Ma, indicating that the depositional age of the Zhesi Formation is not early than the Middle Permian.

4.1.4 Linxi Formation

Two samples (18SL01-TW1, 18SL01-TW2) on the lithic feldspar sandstone of the Upper Permian Zhesi Formation were dated. The zircons of sample 18SL01-TW1 are prismatic or round (Figure 6). The particle size is about 50–120 μm , and the aspect ratio is between 2 : 1–1 : 1. The internal texture of the zircon has a clear oscillating growth zone. The Th/U ratios are greater than 0.5, indicating that the detrital zircons have a magmatic rock origin. LA-ICP-MS dating of 100 zircon points was performed on the sample 18SL01-TW1 (Table S1, Figure 10). The age spectrum shows five group peak ages, including 274 $\pm$ 3 Ma ($n = 75$), 327 $\pm$ 4 Ma ($n = 9$), 469 $\pm$ 5 Ma ($n = 11$), 531 $\pm$ 5 Ma ($n = 3$) and greater than 1 800 Ma ($n = 2$). The youngest zircon age is 258 Ma.

The sample 18SL01-TW2 is mostly round. The size is about 50–100 μm (Figure 6). The aspect ratio is between 2 : 1–1 : 1. The zircons have an obvious oscillating growth zone. Ninety-nine zircon ages indicate the multiple peak ages (Table S1), which are 243 $\pm$ 3 Ma ($n = 15$), 262 $\pm$ 3 Ma ($n = 34$), 327 $\pm$ 5 Ma ($n = 14$), 407 $\pm$ 4 Ma ($n = 14$), 486 $\pm$ 5 Ma ($n = 13$), 824 $\pm$ 7 Ma ($n = 8$), 1 159 $\pm$ 12 Ma ($n = 1$), and 1 389 $\pm$ 23 Ma ($n = 1$). The minimum ages of the detrital zircons of the two samples from the Linxi Formation are 241 and 258 Ma.

4.2 Geochemistry

In this study, geochemistry of the matrix of the tectonic mélange in the Dashizhai area, the silty slate and rhyolite of the Shoushangou Formation, the silty slate of the Zhesi Formation, and the debris feldspar sandstone of the Linxi Formation were analyzed.

The clastic rocks in the Permian sedimentary basin of Dashizhai show low-grade metamorphism. The high field

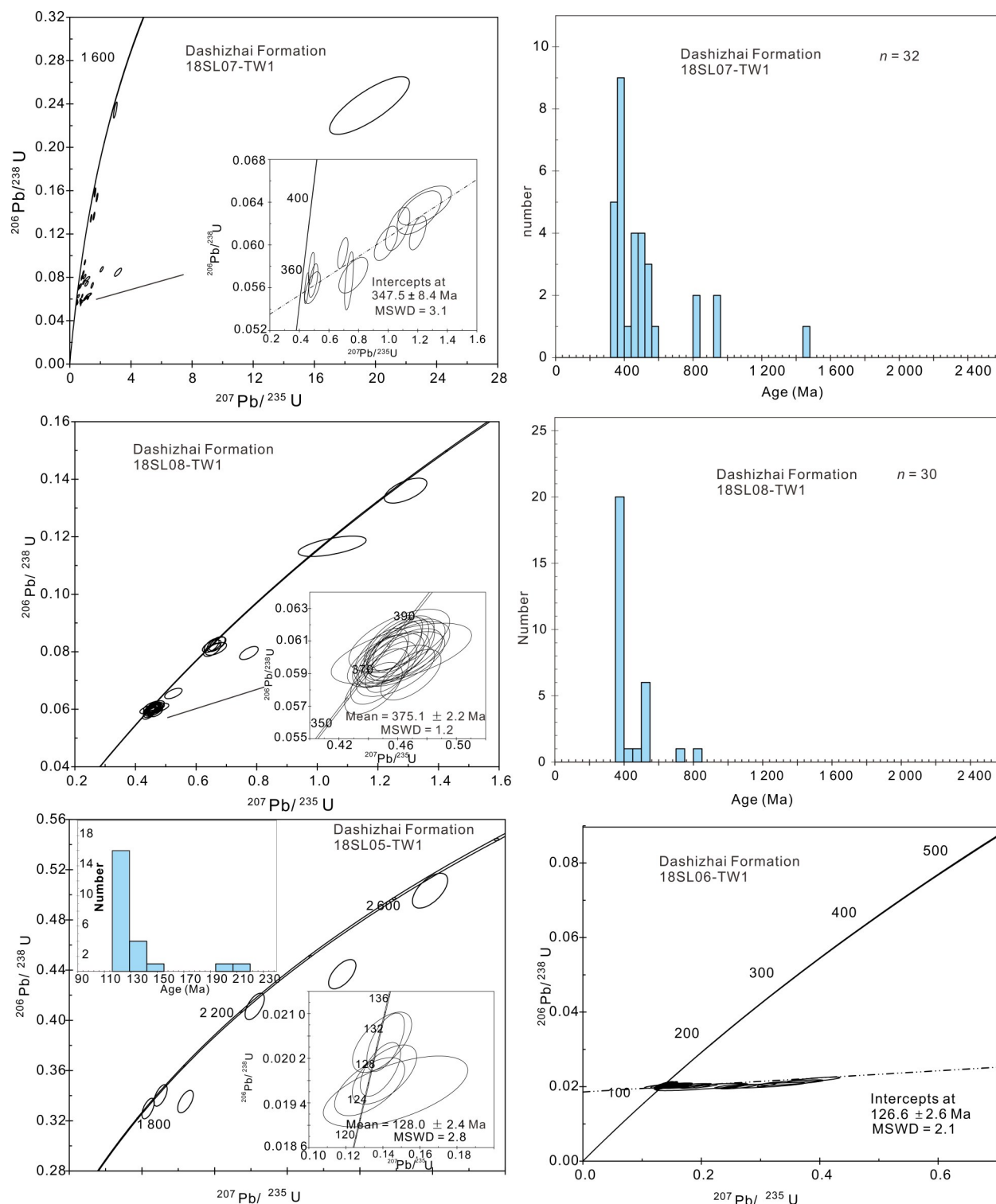


Figure 7. Zircon $^{207}\text{Pb}/^{235}\text{U}$ - $^{206}\text{Pb}/^{238}\text{U}$ Concordia diagrams of samples from the Dashizhai Formation in Dashizhai Basin. MSWD. Mean square of weighted deviates.

strength elements and rare earth elements of low-grade metamorphic rocks can distinguish their provenance (Taylor et al., 1985). The analysis results of major and trace elements of each formation are shown in Table 1.

4.2.1 Dashizhai Formation

Three samples of argillaceous siltstone in the Dashi-

zhai structural mélange (Table S2) show that the major elements have medium SiO_2 (60.58 wt.%–64.56 wt.%) with an average value of 62.56 wt.% and high Al_2O_3 (15.44 wt.%–18.67 wt.%) with an average value of 16.98 wt.%. They are plotted in the shale area in the sedimentary rock classification diagram (Figure 11a). The total amount of rare earth elements is low ($\sum \text{REE} = 102.71$

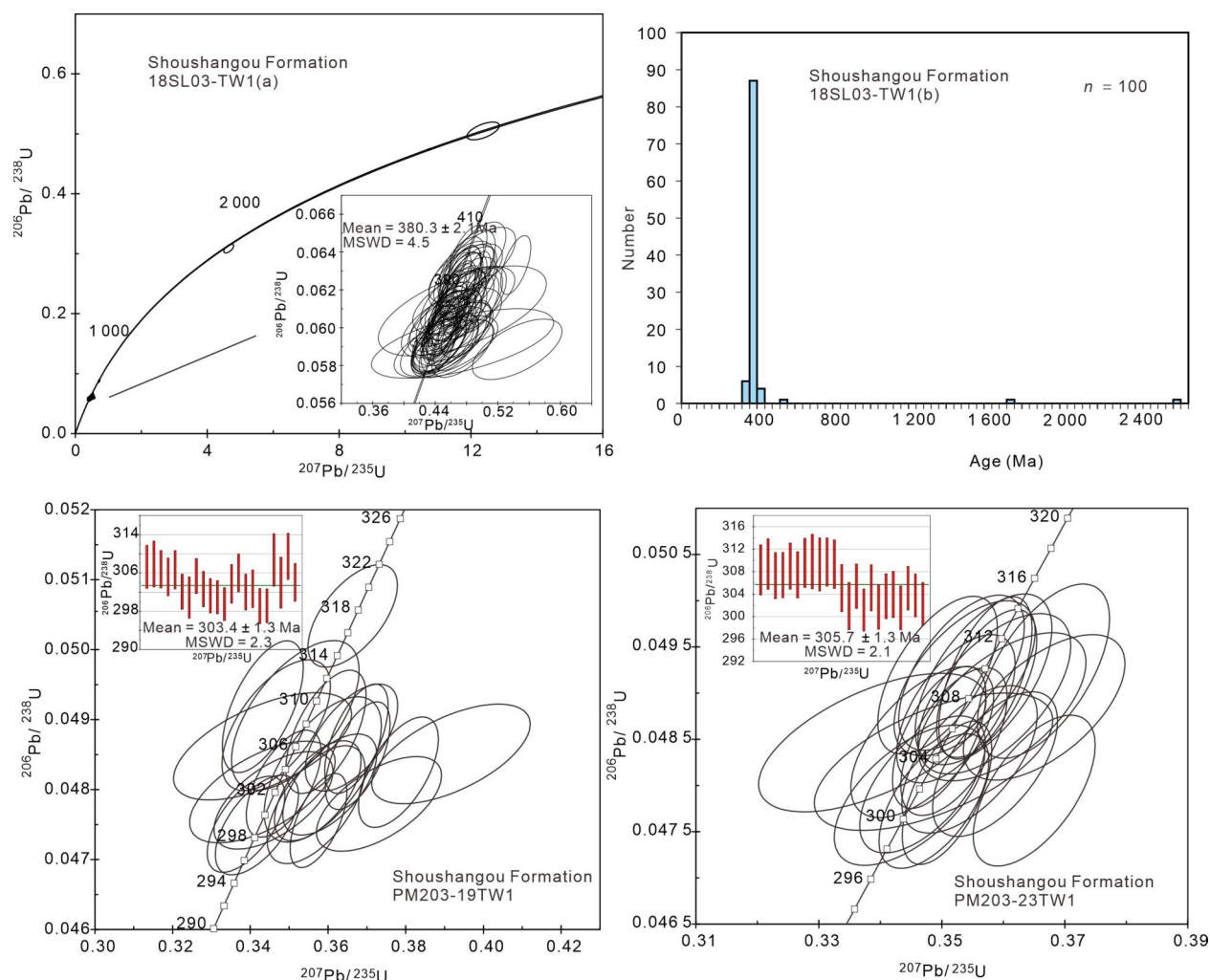


Figure 8. Zircon $^{207}\text{Pb}/^{235}\text{U}$ - $^{206}\text{Pb}/^{238}\text{U}$ Concordia diagrams of samples from the Shoushangou Formation in Dashizhai basin. MSWD. Mean square of weighted deviates.

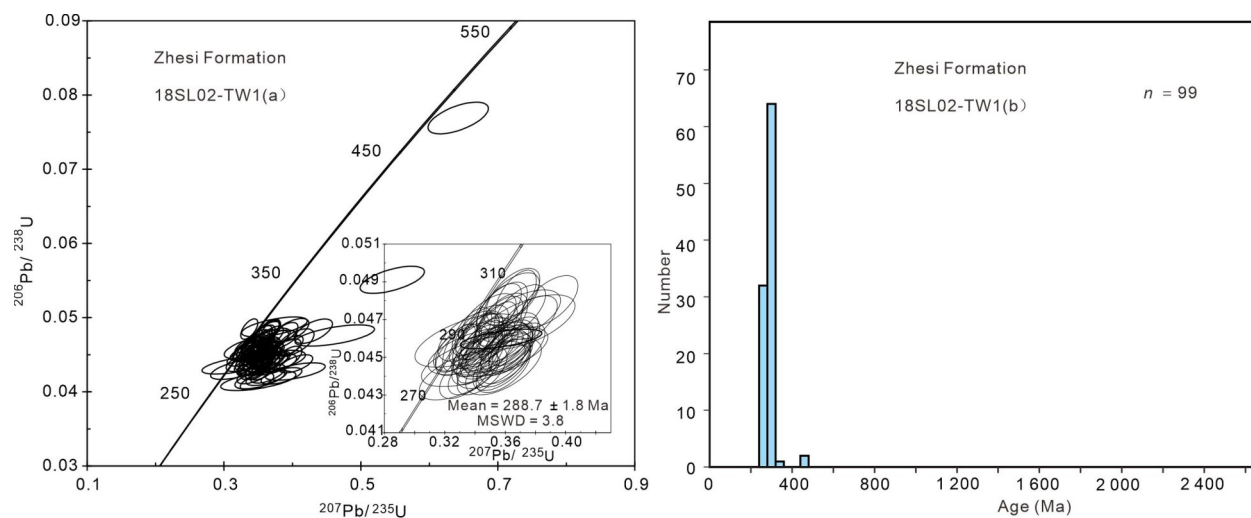


Figure 9. Zircon $^{207}\text{Pb}/^{235}\text{U}$ - $^{206}\text{Pb}/^{238}\text{U}$ Concordia diagrams of samples from the Zhesi Formation in Dashizhai basin. MSWD. Mean square of weighted deviates.

ppm–176.08 ppm). The standardized diagram of North American Shale (Figure 12a) shows that the light rare earth elements are enrichment ($\text{La}/\text{Yb}_N = 2.67 - 6.54$),

whereas Eu is depleted ($\delta_{\text{Eu}} = 0.61 - 0.75$). Two samples have a weak negative Ce anomaly, whereas one sample has a positive Ce anomaly ($\delta_{\text{Ce}} = 2.03$). Trace elements

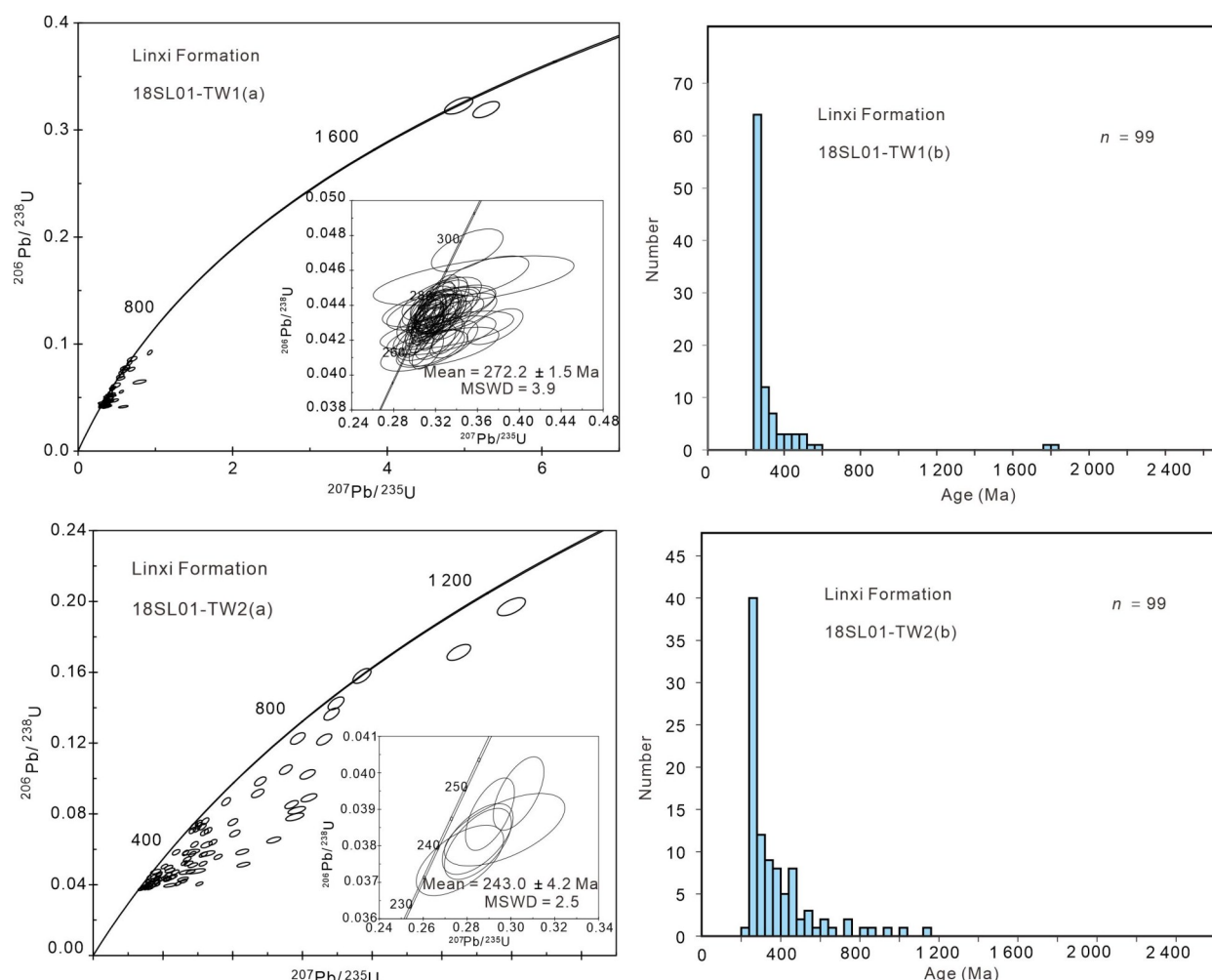


Figure 10. Zircon $^{207}\text{Pb}/^{235}\text{U}$ - $^{206}\text{Pb}/^{238}\text{U}$ Concordia diagrams of samples from the Linxi Formation in Dashizhai Basin. MSWD. Mean square of weighted deviates.

show homogeneous (Figure 12b) Th (5.48 ppm–9.54 ppm) and Zr (103.9 ppm–453.9 ppm) concentrations. The low ratios of La/Sc, Th/Sc, and La/Co indicate that the content of mafic sources is rare (Cullers, 2000).

4.2.2 Shoushangou Formation

Twelve samples of tuffy silty slate of the Shoushangou Formation were analyzed (Table S2). The major elements are medium SiO_2 (60.47 wt.%–68.04 wt.%) with an average value of 64.29 wt.% and high Al_2O_3 (16.26 wt.%–19.6 wt.%) with an average value of 17.62 wt.%. They are all plotted in the shale and wacke areas in the sedimentary rock classification diagram (Figure 11a). The total amount of rare earth elements is high ($\sum \text{REE} = 152.14 \text{ ppm}$ – 220.03 ppm), and the standardized diagram of North American Shale (Figure 12a) shows light rare earth enrichment ($(\text{La}/\text{Yb})_N = 7.43$ – 9.99). Eu is a negative anomaly ($\delta_{\text{Eu}} = 0.52$ – 0.72), and Ce is consistent ($\delta_{\text{Ce}} = 0.96$ – 1.06). The trace elements (Figure 12b) show homogeneous Th (9.37 ppm–13.37 ppm), Zr (175.4 ppm–273.2 ppm), and Co (7 ppm–13.6 ppm) concentrations, with low La/Sc (1.85–2.7), Th/Sc (0.68–0.96), and La/Co (2.72–5.49) ratios.

Six rhyolite samples from the Lower Permian Shoushangou Formation were analyzed (Table S2). The geochemical data are plotted in rhyolite area in the $\text{K}_2\text{O} + \text{Na}_2\text{O}$ vs. SiO_2 diagram (Figure 11b). The rocks have high SiO_2 (74.48 wt.%–78.21 wt.%), potassium ($\text{K}_2\text{O}/\text{Na}_2\text{O} = 1.07 \text{ wt.}\%$ – $1.43 \text{ wt.}\%$) and alkalinity ($\text{K}_2\text{O} + \text{Na}_2\text{O} = 7.25 \text{ wt.}\%$ – $8.68 \text{ wt.}\%$), as well as poor TiO_2 (0.12 wt.%–0.22 wt.%), CaO (0.07 wt.%–0.65 wt.%), P_2O_5 (0.01 wt.%–0.05 wt.%), MgO (0.11 wt.%–0.52 wt.%), and FeO_T (1.39 wt.%–1.97 wt.%). The rocks are peraluminous with $\text{A}/\text{CNK} = 1.41$ – 1.75 and sub alkaline series with Ritman index = 1.58–2.22. $\sum \text{REE}$ (59.70 ppm–146.91 ppm) is low with $(\text{La}/\text{Yb})_N = 2.56$ – 7.01 (Figure 12c). The degree of fractionation is moderate ($\delta_{\text{Eu}} = 0.44$ – 0.54) with obvious negative Eu abnormal. The trace elements of the rocks (Figure 12d) are consistent, showing that they are rich in large ion lithophile elements and depleted in high field strength elements.

4.2.3 Zhesi Formation

Four samples of feldspar lithic sandstone from the Zhesi Formation were analyzed (Table S2). The major elements of SiO_2 (66.21%–74.76%) and Al_2O_3 (9.94%–

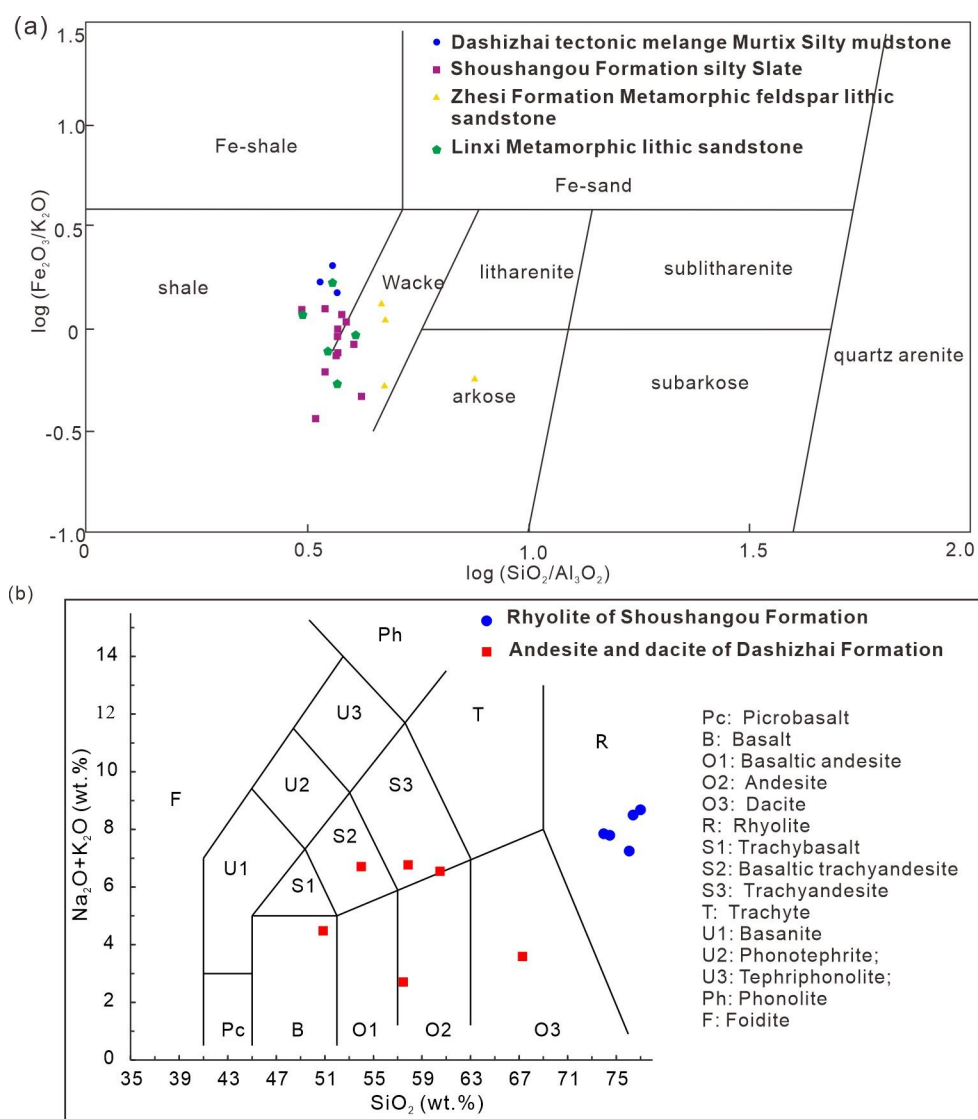


Figure 11. (a) $\log (\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ vs. $\log (\text{SiO}_2/\text{Al}_2\text{O}_3)$ plot for sedimentary rocks in Dashizhai Basin (after Herron, 1988); (b) $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. SiO_2 plot for volcanic rocks in Dashizhai Basin (after Le Maitre, 1989).

15.24%) have high concentrations. They are all plotted in the wacke and feldspar sandstone areas (Figure 11a). The total rare earth elements are low ($\sum \text{REE} = 75.66$ ppm–164.62 ppm). The standardized diagram of North American Shale (Figure 12a) shows that light rare earth elements are enriched ($\text{La}/\text{Yb}_N = 5.54$ –7.25). Eu has a negative abnormality ($\delta_{\text{Eu}} = 0.68$ –0.91), and Ce is consistent ($\delta_{\text{Ce}} = 0.95$ –1.13). Trace elements (Figure 12b) have various Th (4.36–9.86 ppm), Zr (313.0 ppm–516.3 ppm), and Co (1.8 ppm–7.5 ppm) concentrations. La/Sc (2.30–4.10), Th/Sc (0.78–1.17) and La/Co (2.70–12.30) ratios have wide ranges.

4.2.4 Linxi Formation

Five samples of feldspar sandstone from the Linxi Formation were analyzed (Appendix Table A2). The major elements have medium SiO_2 (60.05%–64.66%) and high Al_2O_3 (16.2%–19.46%). They are all plotted in the shale and wacke areas (Figure 11a). The total amount of

rare earth elements ranges from 124.95 ppm to 192.42 ppm. The standardized diagram of North American Shale (Figure 12a) shows heavy rare earth enrichment deplete ($\text{La}/\text{Yb}_N = 6.07$ –7.97). Eu has a negative anomaly ($\delta_{\text{Eu}} = 0.67$ –0.93), and Ce is consistent ($\delta_{\text{Ce}} = 0.97$ –1.04). Trace elements (Figure 12b) show low Th (6.57 ppm–10.05 ppm) and high Zr (440.2 ppm–499.4 ppm) and Co (7.3 ppm–20.0 ppm) concentrations with low La/Sc (1.97–2.75) and Th/Sc (0.52–0.73) ratios. The La/Co (1.55–4.36) ratios are varied.

5 DISCUSSION

5.1 Deposition Age of the Dashizhai Basin

The detrital zircon U-Pb ages (Table S1) from the sedimentary of the Dashizhai Formation, Shoushangou Formation, Zhesi Formation, and Linxi Formation are plotted in Figure 13. The ages of the sedimentary rocks are 294 ± 1 and 287 ± 1 Ma, and the age of tuff is 281 ± 1 Ma. These ages indicate that the tectonic mélange was

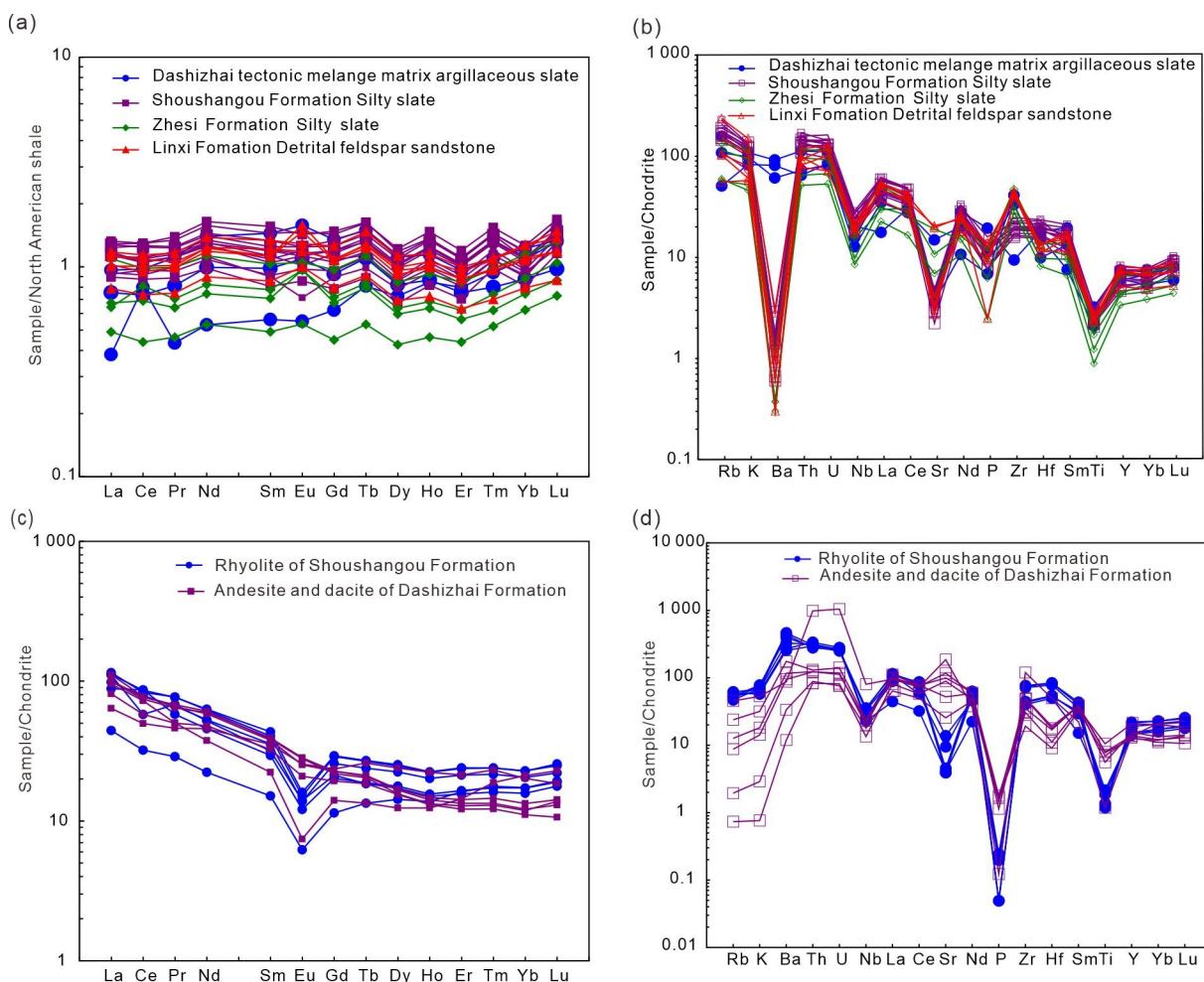


Figure 12. (a) Normalized rare earth element (REE) diagram for sedimentary rocks; (b) normalized trace elements spider diagram for sedimentary rocks; (c) normalized rare earth element (REE) diagram for volcanic rocks; (d) normalized trace elements spider diagram for volcanic rocks. North American shale-normalized values are from Haskin and Haskin (1966); chondrite-normalized values are from Boynton (1984).

formed in the Late Permian (Zhou et al., 2018). Dashizhai andesite was formed at 294 ± 1 Ma (Zhou et al., 2018), dacite was formed at 313 ± 2 and 288.4 Ma. These ages are similar to the volcanic rocks in the region.

Dashizhai Formation: The age spectrum of detrital zircons from the Dashizhai Formation in Wuchagou area can be divided into two groups. Although there are few data obtained in this work, the age of 63 zircons obtained from the two samples may have constrained their formation age and provenance. The Dashizhai Formation can be compared with the strata of Hongquanhe Formation in Northeast China. The silty slate of Ermustaigou and the andesite of Shuipaodangou Formations can be classified into Early Cretaceous Baiyingolao Formation.

Shoushangou Formation: The age of detrital zircons from the Shoushangou Formation is concentrated at ~ 380 Ma, indicating that the age of the detrital zircons is consistent with the deposition ages. The lower part of the Shoushangou Formation has developed thick-layered conglomerates with high maturity, but the age of this rock cannot be obtained. In the upper part, the formation age of the laminite is $305\text{--}303$ Ma, and the minimum age of the tuff siltstone is 348 Ma. These ages indicate that the

formation ages of the Shoushangou Formation are consistent with Dashizhai Formation.

Zhesi Formation: The age spectrum of detrital zircons from the Zhesi Formation shows that the zircons age with a peak of 279 Ma (40%) are consistent with the age of the volcanic rocks in the Dashizhai Formation. The Zhesi Formation in the study area is rich in paleontological fossils from the Zhesi Fauna, which may constrain the formation age in the Middle Permian. The minimum age is 252 Ma, indicating the formation age of the Zhesi Formation. The stratigraphic unconformity of the Zhesi Formation can be observed on the mélangé which have the Late Permian ages (Zhou et al., 2018). The strata of the Zhesi Formation should also be unconformable on the Shoushangou Formation.

Linxi Formation: The U-Pb age of detrital zircons from the Linxi Formation sandstone samples in the Linxi area of southeastern Inner Mongolia can be divided into four groups, including Carboniferous-Late Permian ($336\text{--}254$ Ma), Early Paleozoic–early Late Paleozoic ($528\text{--}372$ Ma), Mid-Neoproterozoic ($1\,600\text{--}669$ Ma) and Neoproterozoic–Palaeoproterozoic ($2\,534\text{--}1\,600$ Ma). The species and age of the fossils are evident, indicating that the for-

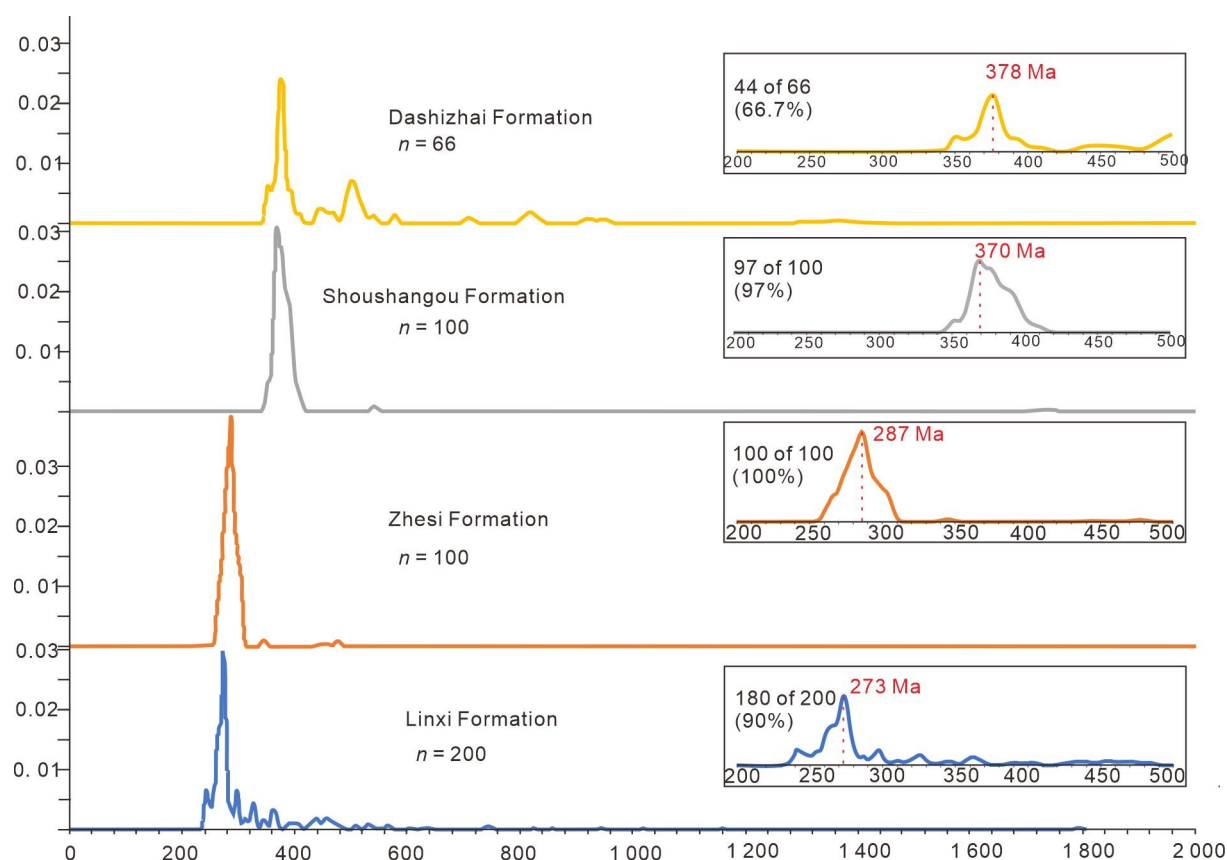


Figure 13. Detrital zircon age spectrum from Dashizhai Basin.

mation of the strata was in the Late Permian. The minimum age of detrital zircons in this formation is 241 Ma, showing that the Linxi Formation has the age of the Early Triassic, which is consistent with the formation age of the group in the Linxi area (Ge et al., 2011). Linxi Formation is unconformity contact with the underlying strata (Wang et al., 2011).

To evaluate the Late Paleozoic Dashizhai sedimentary basins further, a comparison between Dashizhai and well-studied Xiwuqi are as follows: (1) The Upper Carboniferous Benbatu and Amuyan Formations are generally developed in the Xiwuqi area, while the Upper Carboniferous strata are missing in Dashizhai. (2) The Xiwuqi area is unconformity on the Hegenshan ophiolite mélange during the Upper Carboniferous, while the Dashizhai area is unconformity on the Dashizhai tectonic mélange during the Middle Permian. (3) The Jungmubutai and Diyanmiao tectonic mélanges in Xiwuqi area are in fault contact with Shoushan Formation. The age of the mélange block is Late Paleozoic (320–296 Ma, Wang et al., 2017), which is similar to that in Dashizhai area. Therefore, Dashizhai tectonic mélange is formed during Late Paleozoic (311–296 Ma, Zhou et al., 2018). (4) From the bottom to the top, the Late Paleozoic sedimentary strata of Xiwuqi are migration, while the Late Paleozoic strata in Dashizhai area are developed entirely.

5.2 Provenance of the Dashizhai Basin

The geochemical data of the siltstone sample reveal

the sedimentary source (Mao and Liu, 2011). The trace elements have weak various in the diagenetic process, which can reflect the geochemical signature of the parent rocks (Condie, 1993). Roser and Korsch (1986) established a multivariate discriminant diagram based on TiO_2 , Al_2O_3 , Fe_2O_3 , MgO , CaO , Na_2O , K_2O , and can effectively divide four types of provenance areas, including felsic igneous provenance, neutral fire source, quartz sedimentary rock source, and mafic igneous source (Figures 14a, 14b). The sedimentary sources of the Permian sedimentary basin in Dashizhai are felsic or neutral igneous rocks. Inactive REEs and trace elements such as La, Ce, Th, Zr, Nd, Y, Hf, Nb, Sc, Co, and Ti are also significant for identifying clastic rock provenance (Condie, 1998). The La/Th-Hf diagram (Figure 14c) and the Th-Hf-Co diagram (Figure 14d) distinguished the different sources.

The provenance of the Dashizhai structural mélange is featured by upper crust felsic shale and neutral igneous rock. The clastic sediments of the Dashizhai Formation are mainly derived from the Permian volcanic rocks. Detrital feldspar sandstones of the Shoushangou Formation are plotted in felsic or neutral igneous rock areas and are upper-crust shale. Combined with lithostratigraphic data, many sedimentary tuffs are developed in the first member of the Shoushangou Formation, and rhyolite layers are produced in the second member, which is covered by the acidic volcanic rocks of the Dashizhai Formation. These features indicate that the sedimentary clasts of the Shoushangou Formation are mainly derived

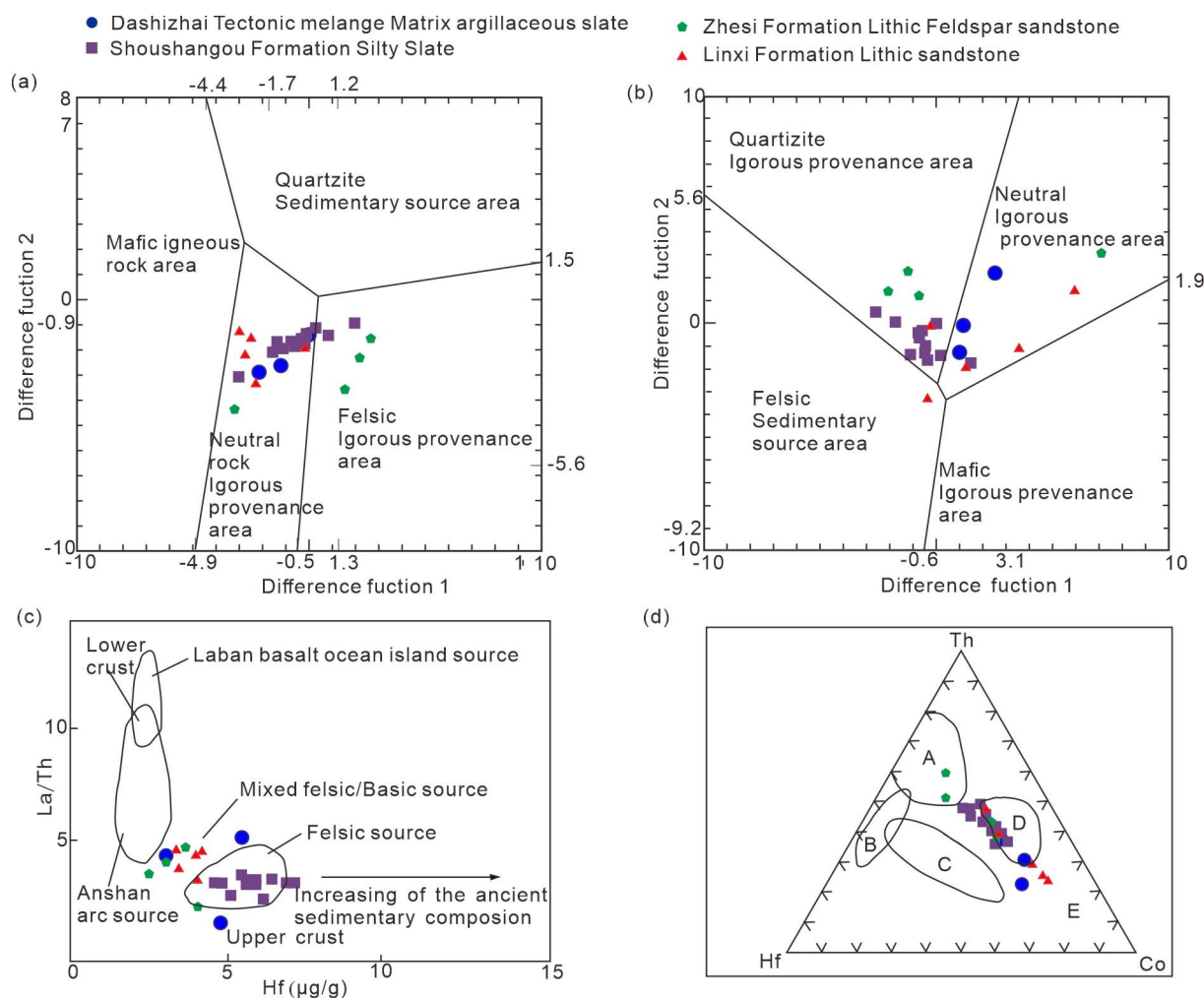


Figure 14. (a), (b) The nature of the provenance area of the Permian Dashizhai strata (Roser and Korsch, 1986); (c) La/Th-Hf diagram (Gu et al., 2002); (d) Th-Hf-Co diagram (Condie, 1989). A. Felsic volcanic rock; B. quartzite sedimentary rock from the craton basin; C. feldspar sandstone; D. shale (upper crust); E. miscellaneous sandstone (island arc).

from the same period volcanic rocks (320–290 Ma). The source of the debris feldspar sandstone of the Zhesi Formation is the felsic igneous rocks. Fossil-bearing carbonate rocks with massive thickness developed in the Zhesi Formation in the study area, indicating that this formation was formed in a stable shallow-water environment (Zhu et al., 2007). The feldspar lithic sandstone of the Linxi Formation is in the felsic igneous rock area, and some data plot in the sedimentary rock area, indicating that the source of Linxi Formation sedimentary sandstone was erosion, transportation and redeposition.

5.3 Tectonic Settings and Implications

The Paleozoic tectonic framework of the Xing'an-Inner Mongolia Orogen is controlled by the evolution of the Paleo-Asian Ocean. Previous works show that the initial subduction of the Paleo-Asian Ocean was likely in Early Ordovician (Li et al., 2011; Xue et al., 2009; Miao et al., 2008). However, the evolution the Paleo-Asian Ocean are still debated. For example, the Paleo-Asian Ocean closed in the Middle Devonian. The Late Paleozoic in the Xing'an-Inner Mongolia Orogen is an extensional back-

ground (Shao et al., 2014; Zhu et al., 2004). The ocean subduction lasted until the Late Carboniferous (Wang et al., 2018) and even to the Late Permian–Early Triassic (Eizenhöfer et al., 2015a, b, 2014; Liu et al., 2013; Jian et al., 2012; Li et al., 2007; Xiao et al., 2003).

Generally, the Hegenshan ophiolite was cited to represent the closure of the ocean in Late Devonian, however, there are many studies about the age of the Hegenshan ophiolite, such as 295 ± 18 Ma from cumulate gabbros, 298 ± 9 Ma from mafic dikes, 244 ± 4 Ma from granodiorite dikes and a 293 ± 1 Ma whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ age from a basalt matrix (Miao et al., 2008), and 354–269 Ma (Eizenhöfer et al., 2015a, b, 2014). These ages represent that the evolution of the Paleo-Asian Ocean may have multi-stages. In this study, the detrital zircons of the Dashizhai Basin indicate that the study area was an extensional setting since the Early Carboniferous. Three Early Permian magmatic rock belts were formed along Erlian-Dongwuqi, Mandula-Sunitezouqi-Xiwuqi and the northern margin of North China Craton. The Erlian-Dongwuqi belt is characterized by A-type granite (Hong et al., 1994). The Mandula-Sunitezouqi-Xiwuqi belt is

characterized by bimodal volcanic rocks (Li et al., 2016; Shao et al., 2015; Chen Y et al., 2014; Chen C et al., 2012; Zhang et al., 2008) and A-type granite (Shao et al., 2015; Shi et al., 2004). The Early Permian intrusive rocks on the northern margin of the North China Craton show the both signature of island arc magmatic rocks (Zhang et al., 2009, 2007) and bimodal volcanic rocks (Shao et al., 2015). Rhyolites and intermediate-basic volcanic rocks in Xilinhote and Xiwuqi show that the period of Late Carboniferous–Early Permian was an extensional setting (Chen et al., 2014; Zhang et al., 2008).

Therefore, we prefer that: (1) The central part of Xing'an–Inner Mongolia Orogen was an extensional stage since the Late Carboniferous. The magmatic rocks of the Late Carboniferous indicate the newly opened ocean basin during Late Carboniferous (Wang et al., 2021). (2) The basin is an extension of Hegenshan ophiolitic mélange belt and the boundary between Xing'an Block and Songliao Block, due to the similar signature between the Lower Carboniferous in Wuchagou area and Hongquanhe Formation (Zhao et al., 2012), which is a product of epicontinental sea developed above Xing'an Block. Shoushangou Formation and Dashizhai Formation should be the products of rift extension.

6 CONCLUSIONS

In this study, the youngest age (347 Ma) of the detrital zircons of the silty slate from the Dashizhai Formation indicates that the sedimentary age is not earlier than the Early Carboniferous. The youngest age (348 Ma) of the detrital zircon of the tuffaceous argillaceous slate from the Shoushangou Formation indicates the sedimentary age of the Shoushangou Formation is not earlier than the Early Carboniferous. The age of abundant paleontological fossils and silty slate clastic (252 Ma) in the Zhesi Formation indicates that the sedimentary age of the Zhesi Formation is not earlier than the Middle Permian. The ages of detrital zircons from the Linxi Formation (241 and 258 Ma) can constrain that the Linxi Formation age is not earlier than Late Permian.

The age of detrital zircons is concentrated at ~290 Ma, which indicates that the formation age of the detrital zircons in the main source of the Dashizhai Formation is the same as the deposition age. The clastic sediments of the Dashizhai Formation were mainly derived from the products of Permian volcanism and were transported to the sedimentary basin to be deposited. The Permian sedimentary basin of Dashizhai was formed in a rift environment, and its sedimentary source came from the Ergun, Xing'an, and Songliao blocks. The Hegenshan–Heihe structural belt is distributed in Dashizhai Basin, forming a splicing belt between the Xing'an and Songliao blocks. The Zhesi Formation was unconformity on the mélange of the Dashizhai Formation during the crust sinking. The absence of the Late Carboniferous strata in the Dashizhai Basin indicates that the study area was an extensional system during the Late Carboniferous.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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